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Thermoeconomic modeling of a small-scale gas turbine-photovoltaic-electrolyzer combined-cooling-heating-and-power system for distributed energy applications

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ABSTRACT

The purpose of this study is to investigate the potential of a small-scale, combined-cooling-heating-and-power system, consisting of a 1 MW_e gas turbine subsystem coupled to a 0.5 MW_e photovoltaic (PV) subsystem for application in Cyprus. The proposed system is completely autonomous, without any interconnections to a central power grid. To allow maximum utilization of the electricity generated by the PV subsystem, an electrolyzer unit is coupled to the system to convert excess renewable electricity to hydrogen. The generated hydrogen is injected to the natural gas supply for the gas turbine. For the generation of useful cooling and heating, the system recovers heat from the flue gas exiting the gas turbine; the recovered heat is supplied to a heat-activated absorption chiller/heater to generate cooling or heating. An electric chiller/heater is integrated to the system to supplement thermal energy when necessary. The thermal energy is supplied to nearby buildings through a district energy network. The annual average primary energy ratio of the proposed system is 0.806. For an assumed system lifetime of 20 years, the lifecycle cost of the proposed system is 11.12 million USD, resulting to a unit cost of electricity at 0.06 USD/kWh, which is a 62% reduction of the current cost in Cyprus. The results of the parametric study suggest that the economic performance of the proposed system is highly dependent on price fluctuations of the unit cost of natural gas, while the specific cost of the electrolyzer unit is also critical. The proposed system could become an important candidate for power and thermal energy generation in Cyprus as a measure to reduce the presently high cost of electricity.

1. Introduction

A proven solution for the development of highly efficient systems is the well-established technology of cogeneration. Cogeneration includes the generation of electricity with multiple engines, all coupled in a single system, or the simultaneous generation of electric energy and heating, i.e. combined-heat-and-power, which can be extended further to include generation of cooling, i.e. combined cooling, heating and power (CCHP) (Arsalis and Alexandrou, 2014, 2015a; Kong et al., 2004; Wang et al., 2011). Decentralized, completely autonomous CCHP systems are a promising solution, since they offer reduced fuel consumption and negligible transmission and distribution losses, as compared to centralized electricity-only power plants. Also heat losses are insignificant, because the serviced buildings receive thermal energy through a short-distanced district energy network. In the case of gas turbine-based systems, cooling energy can be generated through heat-activated absorption chillers coupled with the exhaust of the turbine (Rezaie and Rosen, 2012).

In recent years, photovoltaic (PV) technology has grown because the specific cost of PV panels has dropped, and is expected to drop further in the near future (US Department of Energy, 2016). The price of commercial PV systems is expected to drop down to 1.34 USD/W by 2020, assuming a 75% drop from 2010 median installation prices, leading to an increasing number of new installations worldwide (Darghouth et al., 2016). However, since standalone PV systems cannot match residential or commercial building demand, there is a need to combine PVs with conventional or alternative

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technologies. An example of a hybrid system for distributed generation is the combination of PV and gas turbine technologies to fulfill a load profile (Arsalis et al., 2016). However, such systems can only become viable for future application, if they reach operational schemes with a unit cost of electricity comparable to that of conventional systems. There are certain research areas for these systems, which include system capacity, climatic region, mode of operation (e.g. electricity-led vs. heat-led operation), autonomous vs. semi-autonomous operation, utilization as main prime movers or auxiliary units, etc.

The literature contains several studies where effort was placed on the coupling of PVs with other technologies (conventional or alternative) to form novel hybrid systems. Ameri and Besharati (2016) investigated the modeling of various scenarios for CCHP systems in urban residential areas to determine their optimal capacity and operation. The considered systems included district heating-and-cooling networks, gas turbines, PVs, boilers, absorption chillers and electric chillers. However the proposed system was not autonomous, since it was connected to a central power grid, which allowed import and export of electricity. It was concluded that there is a possibility of reducing fuel costs and CO_2 emissions with a reduction in the energy cost to 40.8%, and a reduction of primary energy consumption to 38.7%, in comparison to the conventional combination of centralized systems and boilers. The lowest payback period was estimated at 57 months, with up to 35.8% savings in emissions. Comodi et al. (2015) modeled a hybrid PV-gas turbine system. The results showed that the proposed system could provide a solution for the intermittent power generation from the PV panels. However the system emitted high on-site emissions, due to its distributed nature. It was concluded that the maximum size of the PV subsystem able to satisfy a day-ahead-fixed power generation was 49 kW_e.

Ebaid et al. (2015) conducted a thermoeconomic study of a hybrid PV-gas turbine system, where the gas turbine was fueled with hydrogen, generated from excess PV power, through electrolyzer stacks, resulting to a nominal power output of 100 MW_e. This resulted to a net profit of 25% of the initial cost, with a unit cost of electricity ranging from 0.12 to 0.16 USD/kWh, and a payback period of 13 and 15 years, respectively. Guandalini et al. (2015) considered hydrogen injection to a centralized natural gas grid, in relation to large-scale wind turbine systems. The work effort was placed on determining the most promising economic scenario for the electrolyzer unit. It was concluded that both the electrolyzer and the gas turbine could improve the recovered wind power. Jaber et al. (2003) modeled a PV-gas turbine hybrid system able to fulfill peak loads. The system performance was evaluated and a cost analysis was conducted for different operating schemes. The results revealed that the system could generate 140% additional power-per-unit of fuel, as compared to a gas turbine-based power plant.

The motivation for the current study is the design and modeling of a novel, fully autonomous total energy system, combining gas turbine, PV and electrolyzer technologies. An attempt is placed on the quantification, both in terms of technical performance and cost, of the operation and applicability of the proposed CCHP system for distributed energy generation. The proposed system is compared to conventional technology, in terms of efficiency, fuel savings, carbon emissions and cost. In the current study, the integration of an electrolyzer unit model provides a new perspective to the design, sizing and operational scheme of the system. This integration aims for the complete utilization of solar energy from the PV subsystem, but also targets the reduction of natural gas consumption, leading to a decrease of the total cost of fuel, and a reduction of carbon emissions. The main system components are modeled in detail, along with a thorough cost analysis and a parametric study to provide insight on the full potential of the proposed system.

Our specific contributions in this study include the following areas:

- An electrolyzer unit is integrated to the system, not only to enable the over-sizing of the PV subsystem, but also to facilitate a separation between supply and demand at the maximum extent possible. In some previous studies, this has often resulted to a restriction in the design of autonomous energy system solutions, while in others, although an electrolyzer unit was integrated to the system, no actual electrolyzer model was included (limited to simplistic approximations). On the contrary, the current study includes a complete electrolyzer model, which enables the extraction of more realistic and accurate simulation data.
- The system model includes modeling of the off-design operational pattern of the proposed system to allow generation of simulation data at part-load conditions.
- Previous research studies have not shown how proposed systems would perform when an actual, varying load profile is applied. Underestimating the performance of a system at off-design conditions leads to misleading results, which cannot be related to operation at real conditions. The analysis in the current study provides simulation data for a whole year of operation, and is not limited by a simulation of the proposed system at design conditions only, or fixed part-load conditions.
- A parametric study is conducted to investigate the significance of key cost parameters with a high degree of uncertainty, namely the unit cost of natural gas, the specific cost of the electrolyzer unit, and the specific cost of the PV subsystem. This allows quantification of the prospects of the proposed system in terms of economic performance, which is the most critical factor for the commercialization of any energy system solution. A detailed economic evaluation of the proposed system is conducted to allow a realistic evaluation of the system potential. The system is compared to conventional technology to show its possible benefits, with the consideration of certain parameters, namely: lifecycle cost, unit cost of electricity, component costs, fuel cost and lifetime.

The paper is organized as follows: Section 2 introduces the system configuration, including the operating principle and assumptions for the system modeling; Section 3 covers a detailed analysis of the modeling methodology for both the subsystem/components and the overall system; Section 4 presents the results, including validation, system sizing, simulation of the base system model and the parametric study; Section 5 summarizes the conclusions extracted from the study.

2. System configuration

The proposed system is shown in Fig. 1. Ambient air is compressed in the air compressor and combustion of fuel with compressed air takes place in the combustor. The generated flue gas drives the gas turbine and electrical energy is generated through an electric generator. Electricity is also generated in the PV subsystem, when solar energy is available. Excess electricity from the PV is used for the generation of hydrogen in the electrolyzer. The generated hydrogen is mixed with natural gas in the fuel mixer. The flue gas exiting the gas turbine is used to generate steam which activates the absorption chiller/heater (ACH). The ACH generates thermal energy which is supplied to the district energy network. When thermal energy from the ACH is inadequate to satisfy demand, additional energy is supplied by the electric chiller/heater (ECH). Finally, the thermal energy is delivered to the air-handling units of the buildings.